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**Abstract**

The abstract will outline the essential topics of the thesis and condense it into a short and digestible package.

A large portion of atmospheric CO2 is sequestered by diatoms through the biological pump. Understanding the biological pump requires accurate prediction of the size-dependant sinking speeds of diatoms. Diatomic sinking speeds can be more accurately calculated through an alternative model to Stokes’ law. Stokes’ law predicts a much higher upper bound of sinking speed than empirical data. The alternative model proposed in this study accounts for differences in densities of different cellular constituents as well as the effect of dynamic viscosity on the sinking speed of diatoms. Using the modified model, an estimate of carbon export out of the euphotic zone can be generated using data gathered from satellites. The resulting estimates are also compared with data gathered from sediment traps that are scattered in the oceans.

**Introduction**

The introduction will give background to the paper, reference relevant papers (Kostadinov et. al 2009, 2016, MIT Seawater Papers, Mouw Dataset), as well as stating the main points of the thesis: The mathematical concepts of Stokes Law (force balance between gravity and the friction of the fluid), satellite data and its resulting plots, comparisons sediment trap data. It will also outline the general structure for the paper.

**Carbon Flux and Its Importance**

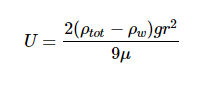
Carbon is exchanged between many systems throughout the world. A prominent form of Carbon that is exchanged between many ecosystems is CO2. CO2 is important to study because it is fixed by phytoplankton at the ocean surface into biomass. Plankton sink from the surface mixed layer into the deeper ocean. The so-called “biological pump” serves as a method for the sequestration of atmospheric carbon into the deep ocean. Estimating carbon export within the ocean is difficult, with some studies predicting approximately 6 Petagrams of carbon yearly exported from the euphotic zone (Siegel et al 2014). Furthermore, sediment trap data about phytoplankton sinking speeds is sparse in space and time. Satellite data offers superior spatial and repetitive coverage, which motivates the creation of models that can estimate carbon export from satellite data.

**Stokes Law and Predicting Sinking Speeds**

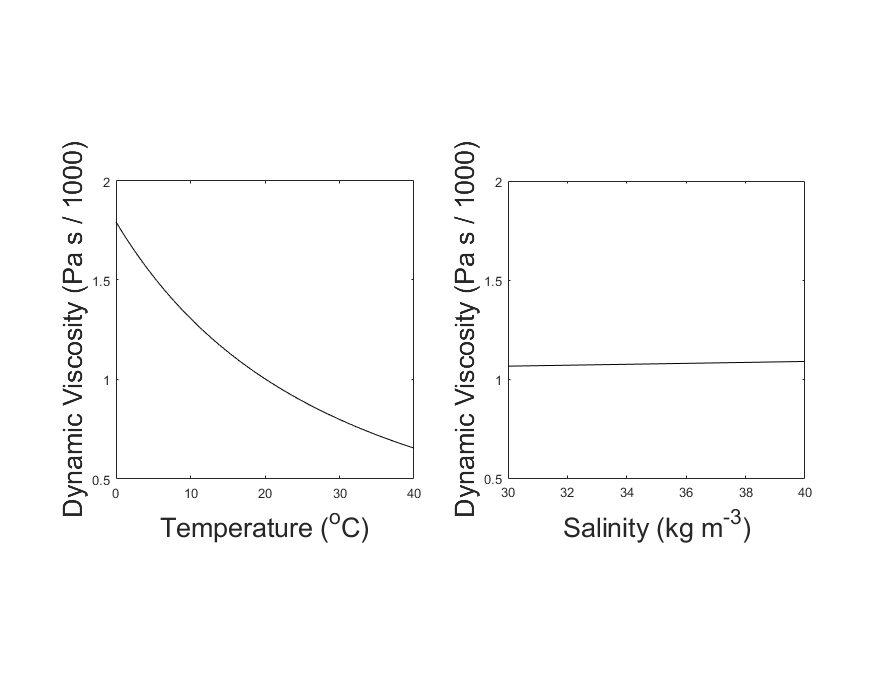
**A****. Particle Size and Sinking Speed  
 i. Basic Stokes Law**

Sinking speeds of phytoplankton are often estimated by Stokes’ law, which predicts sinking velocities that scale by an exponent of 2 in relation to its radius. Sinking plankton particles satisfy the prerequisites of Stokes’ Law, as they are small, slow moving spherical objects that move slowly in relation to its outside medium. Using a newer model predicts that diatoms, which synthesize approximately half of the ocean’s fixed carbon (Nelson et al 1995; Field et al 1998, cited within Miklasz et al 2010), may follow a more complex extended Stokes Law that accounts for the differing densities of diatomic components (Miklasz and Denny 2010).

The classic stokes model predicts that a sinking particle’s speed (U) is:

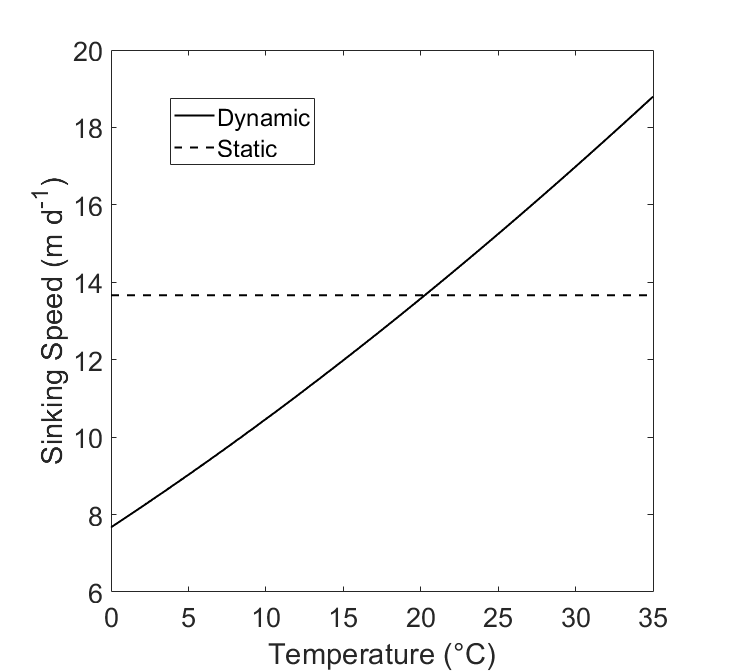


Where ρtot is the density of the particle, ρw is the density of the surrounding liquid (in this case water), r is the radius of the particle, g is the constant of gravitational acceleration (9.8 m s-2), and μ is the dynamic viscosity of surrounding liquid (water).The extended model presented by Miklasz and Denny (2010) assumes constants of ρw = 1023 kg m-3 and μ = 1.07 x 10-3 Pa s, which represents the density and dynamic viscosity of water at 20°C and 33 g L-1 salinity, respectively. Stokes’ law holds up for particles with small Reynolds numbers (Re < 1), which describes all particles mentioned in this paper. Since both dynamic viscosity and water’s density varies with temperature and salinity, it is important to consider both variables within our calculation. However, because the range at which water’s density varies with respect to temperature and salinity differences is so small, we can safely assume water to have a constant density of ρw ≈ 1023 kg m-3. Since dynamic viscosity is a large factor in this equation (Fig. 1), we include the variation of dynamic viscosity within our calculation. Dynamic viscosity (μ) is a key variable in Stokes Law that is overlooked. Miklasz and Denny (2010) assume that dynamic viscosity remains constant. Dynamic viscosity depends on temperature and salinity, and is dominated by the effects of the former (Fig. 1). The effect of dynamic viscosity is also apparent over the relevant temperature range (Fig 2). In order to calculate the change in dynamic viscosity, we use a seawater toolbox that estimates dynamic viscosity of seawater given temperature and salinity (Sharqawy et al 2010). Using this basic Stokes’ law model, sinking speed ( “U” ) is estimated for diatoms with small, medium, and large radii, with values of 5 μm, 10 μm, and 20 μm, respectively (Fig. 3). The sinking velocity of each particle increases by an exponent of 2, which greatly overestimates the sinking speed of larger particles.

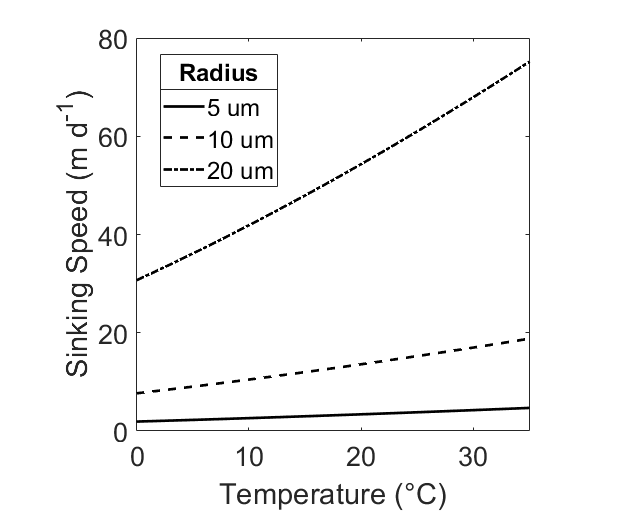
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**Figure 1:** Variation in Dynamic Viscosity of Seawater (μ). Viscosity is plotted against temperature, while holding salinity constant at 35 kg m-3 (left). Viscosity is also plotted against salinity, while holding temperature constant at 20oC (right). Over the normal range of each variable, the change in viscosity is dominated by the effect of Temperature.

**(viscosityplot.m)**



**Figure 2:** The hypothetical sinking speed (“U”) of two cells with identical structure, calculated with and without dynamic viscosity. The solid line (“Dynamic”) represents a model that uses the effect of temperature as it increases from 0°C to 35°C. The dashed line (“Static”) represents a sinking The cell is plotted where r = 10 μm and has a uniform cell density of ⍴tot = 1800 kg m-3.

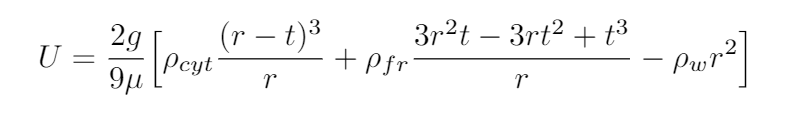
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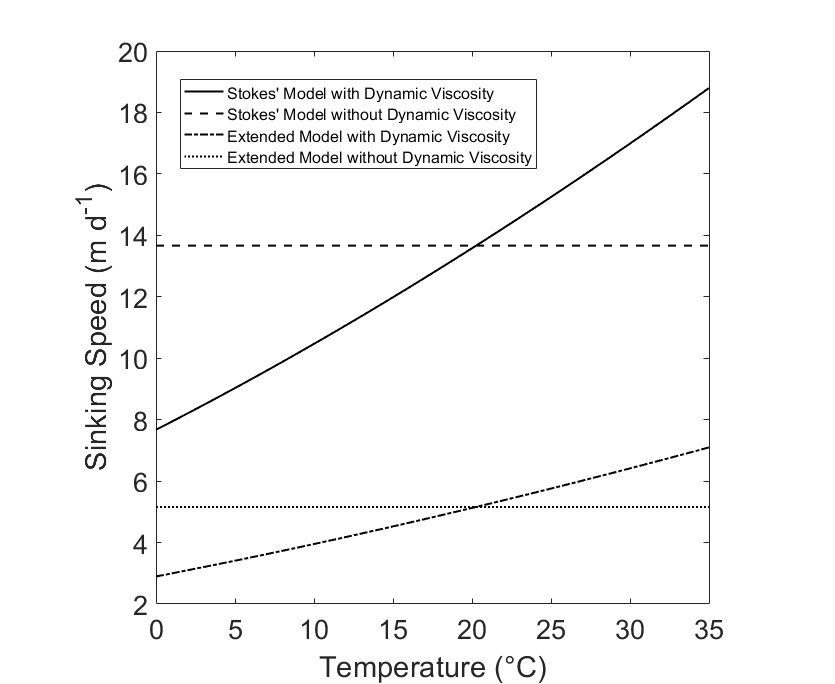
**Figure 3:** Sinking speed (U) in meters per day, calculated by Stokes’ Law. Hypothetical radius values of r = 5 μm (dashed), r = 10 μm (solid), and r = 20 μm (dot / dash) are displayed. Temperature range is 0oC ≤ T ≤35oC, Salinity S = 35 ppt, total cell density ⍴tot = 1800 kg m-3.

**(SpeedPlot\_Viscosity\_Density\_Temperature.m)**

**ii. Extended Stokes Model**

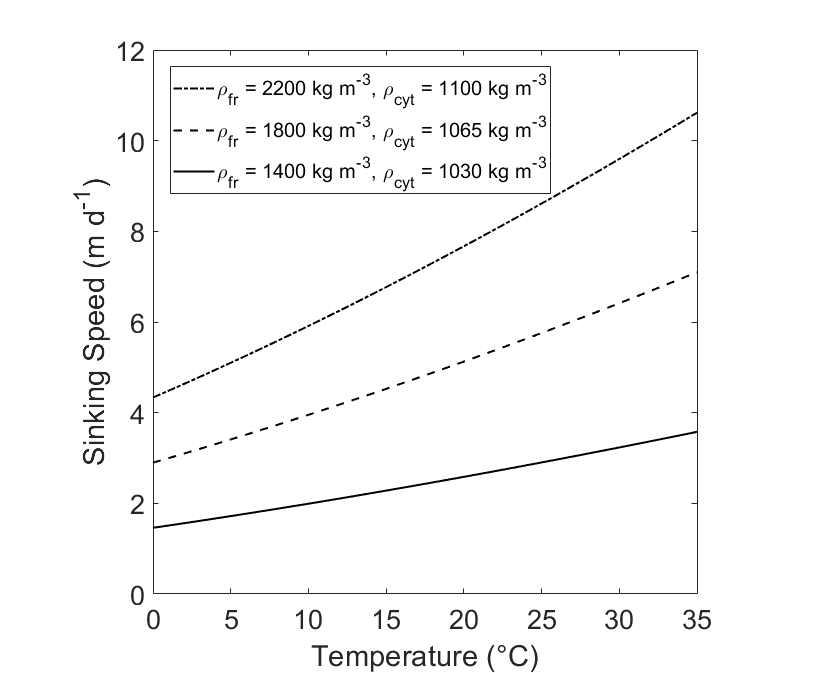
Stokes Law is defined for a spherical particle with uniform density, which does not perfectly describe a diatom’s structure. A diatom may have a hard, dense silicate frustle as well as a less dense cytoplasmic core. Diatomic frustles may constitute up to 70% silica, which is much denser than water (2500 kg m-3). The cytoplasm is less directly studied, with no direct measurement. The density of cytoplasm is said to be in the range of 1030 to 1100 kg m-3 (Smayda 1970).



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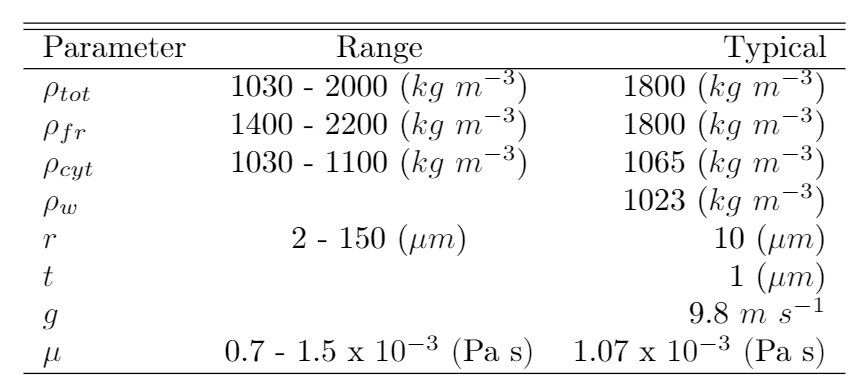
**Figure 4:** Comparisons between Stokes Model and Extended Model. Temperature range is 0oC ≤ T ≤ 35oC, Salinity S = 35 ppt. The basic Stokes Model assumes a cell radius of r = 10 μm and a uniform cell density of ⍴tot = 1800 kg m-3 (“Stokes’ Model”). The Extended Model assumes a cell radius of r = 10 μm, a frustle thickness of t = 1 μm, a cytoplasm density of ⍴cyt =1065 kg m-3, and a frustle density of ⍴fr = 1800 kg m-3 (“Extended Model”). Each model is presented with and without the influence of dynamic viscosity.

**(StokesDennysPlot.m)**

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**Figure 5:** Comparison of Sinking Speed (U) of diatoms at different densities. Sinking Speeds are calculated using the Extended Model. The hypothetical diatoms have radius r = 10 and frustle thickness t = 1 μm

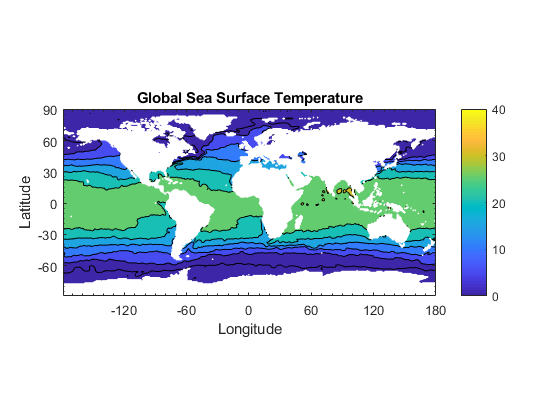
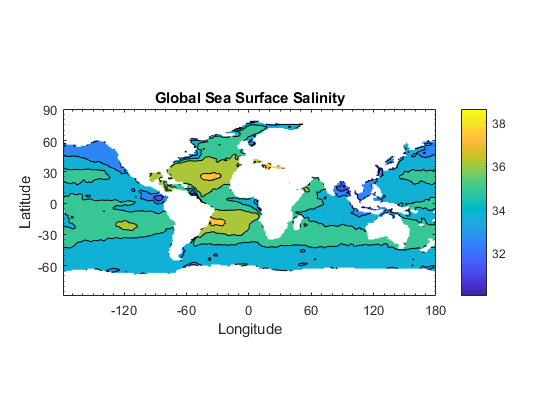
**(VariableDensity.m)**

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**(LaTeX doc)**

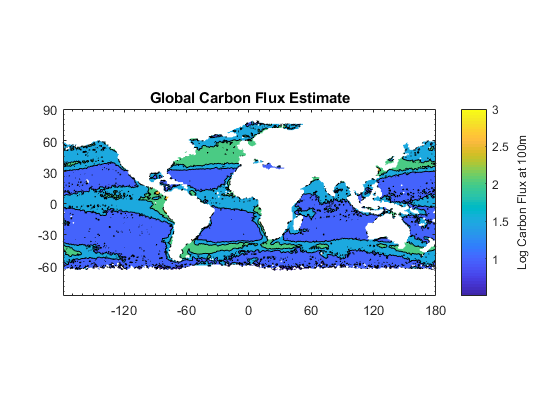
**B. Global Maps of Important Environmental Variables that are measured by satellite (T, S, μ)**

Dynamic viscosity is dependant on salinity and temperature. Using data gathered by satellites, we generate a yearly average sea surface salinity and sea surface temperature model.



(C\_biomass.m)

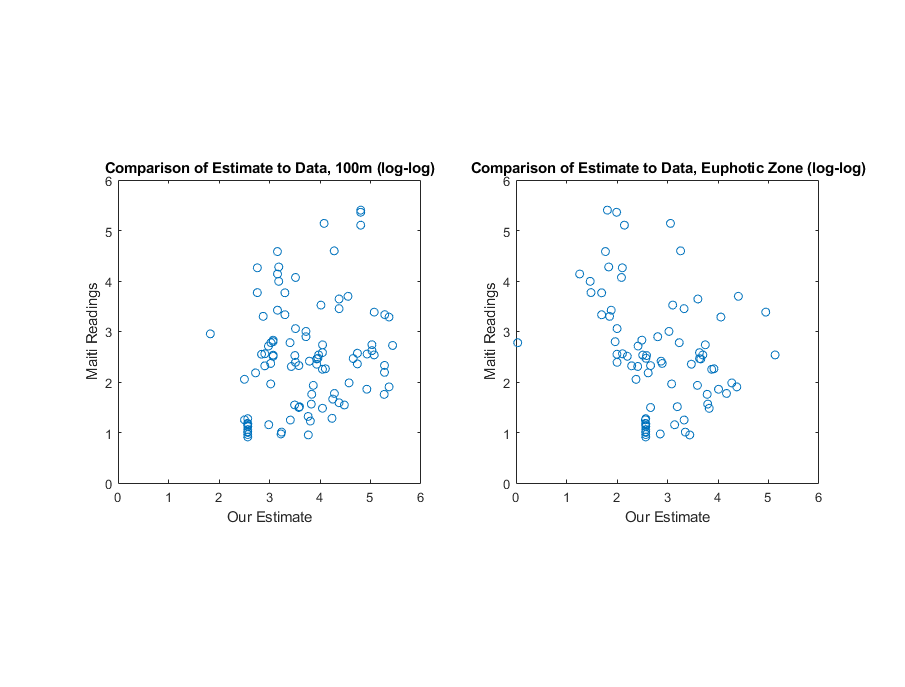
C. Particle Size Distribution and Global Carbon Flux Estimates

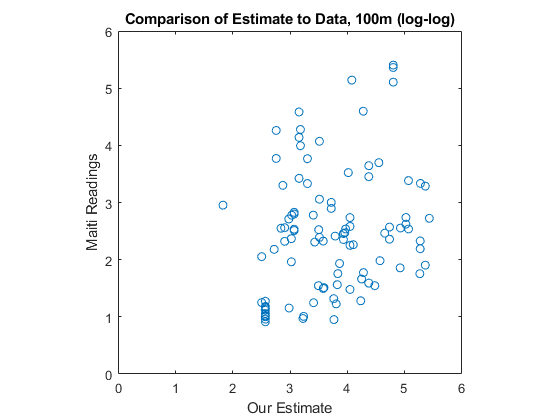


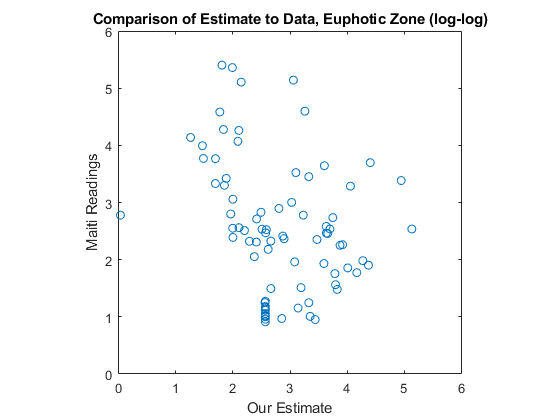
(C\_Biomass.m)

**Sediment Trap Data**

**Comparisons Between Data**





(C\_biomass.m)

**Discussion**

**Citations**

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